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Energy Modelling of Thermal Oil Based Cooking System

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Abstract

Thermal oils as heat transfer fluid have wide applications in various industries such as chemical, oil and gas, manufacturing, food processing, etc. In this paper, energy model is developed for thermal oil based cooking system. This cooking system is established at Prajapita Brahmakumaris Ishwariya Vishwa Vidyalaya, Shantivan, Abu Road, Rajasthan, India with maximum capacity of cooking food of 40 000 guests. The proposed model is dynamic in nature based on Euler method for numerical procedure. Energy model can be used further to analyze thermal oil based cooking system, and for synthesizing energy conservation scheme, which may results in energy savings.

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Keywords: Energy modelling; Thermal oil, process integration, energy conservation

1. Introduction

Energy savings opportunities are more in integrated systems than individual, which reduces fuel cost and improves greener footprints (Bade and Bandyopadhyay 2014). Indirect integration employs intermediate fluids such as steam or thermal oil for heat transfer. Typically, latent heat of steam is used for process heating purpose, which offers less heat transfer opportunity compared to thermal oil for same temperature range (Bade and Bandyopadhyay 2014) and it operates in extreme climatic conditions. Further, for high temperature applications, thermal oil system requires lower pressure with less corrosion, improved operational flexibility, better control etc. Due to these reasons, thermal oil is preferred over steam. In this paper, energy model is developed for thermal oil based cooking system. This model can be used further to analyze cooking system and to synthesize various energy conservation opportunities. Thermal oil based cooking system is established at Prajapita Brahmakumaris Ishwariya Vishwa Vidyalaya, Shantivan, Abu Road, Rajasthan, India in 2011. This system is the state of art unique cooking facility with additional features such as safety, control, hygiene, and improved cooking environment for

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dinning capacity of maximum 40 000 people. The cooking system operates thrice in a day with average working duration of 8-13 hrs.

2. Construction and working of cooking system

The layout of thermal oil based cooking system is shown in Figure 1. This cooking system uses Therminol 55 as thermal oil. The main components are as follows: oil heater, heat exchangers such as *kadhai* (cooking/frying pans), a roaster, *tava* (hot plates), etc. (details given in Appendix: Table 1)

Nomenclature

C	thermal heat capacity (kJ/K)	Cp	specific heat at constant pressure (kJ/kg K)
CV	net calorific value (kJ/kg)	$\dot{m}$	mass flow rate (kg/s)
Q	heat duty (kW)	T	temperature (K)
t	time (s or hrs)	U	overall heat transfer coefficient (W/m^2 K)
A	heat transfer area (m^2)	Δ	difference
η	combustion efficiency		

Subscripts

a	air	b	oil heater
c	combustion	o	outlet
r	hot plates (*tava*)	v	cooking/frying pans (*kadhai*)

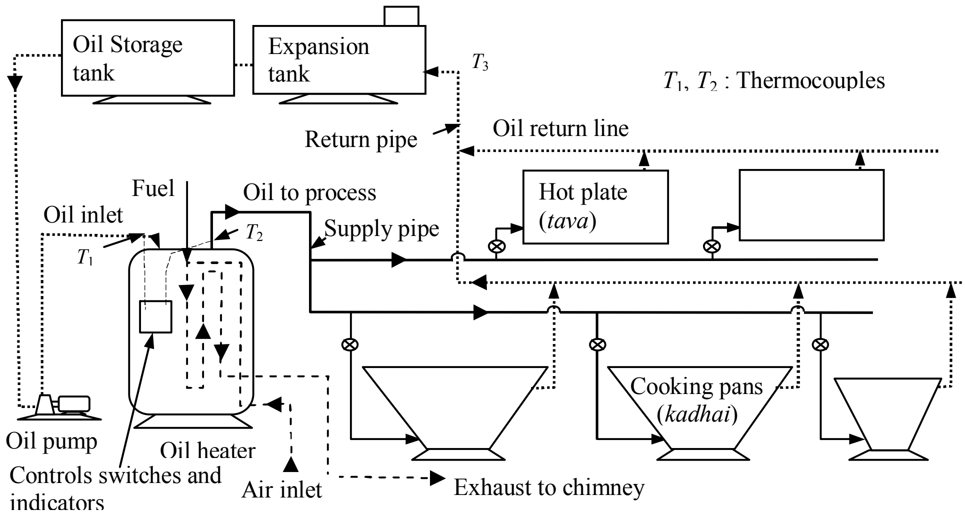

Figure 1: Layout of thermal oil based cooking system with various components

3. Energy modeling and analysis of cooking system

Energy modelling is important to account complete energy flow for improving energy efficiency. To develop energy model of thermal oil based cooking system, all *kadhai* used for vegetable cooking are replaced by single equivalent heat exchanger with thermal storage of heat capacity, C_v (product of mass and specific heat capacity). Similarly, all *tava* are replaced by equivalent single heat exchanger with thermal storage of heat capacity, C_r as shown in Figure 2. Oil heater is modelled as heat exchanger with thermal storage of heat capacity C_b, receives heat duty Q_b by combustion of fuel at efficiency η_c. Therminol 55 is heated up to maximum set temperature limit (T_1) by heat duty Q_b. There are two temperature control switches to limit temperature of Therminol 55 (T_1 and T_2) placed at inlet and outlet of oil heater so that Therminol 55 is maintained in safe temperature limit and at the same time satisfy process requirements. As soon as, the outlet temperature reaches set value (543/548 K), burner flame goes in to low flame operation (oil heater gives only 33% of the full rated heat output). The burner goes to high flame again, as soon as outlet temperature drops below the set value (543/548 K). Similarly, if inlet temperature of Therminol 55 reaches set value (518/523 K), the burner shuts off and there can be no heat output. The burner again switches on as soon as inlet temperature drops below the set value (543/548 K). It is to be noted that during data collection, thermal oil did not crossed upper limit and due to lower limit, fired heater was switched on and off. Thermal storage of heat capacity C_s is considered for combined storage and expansion tanks. Heat loss to atmosphere by convection is product of thermal conductance (product of overall heat transfer coefficient, U and heat transfer area, A) and difference of temperatures between system and ambient air.

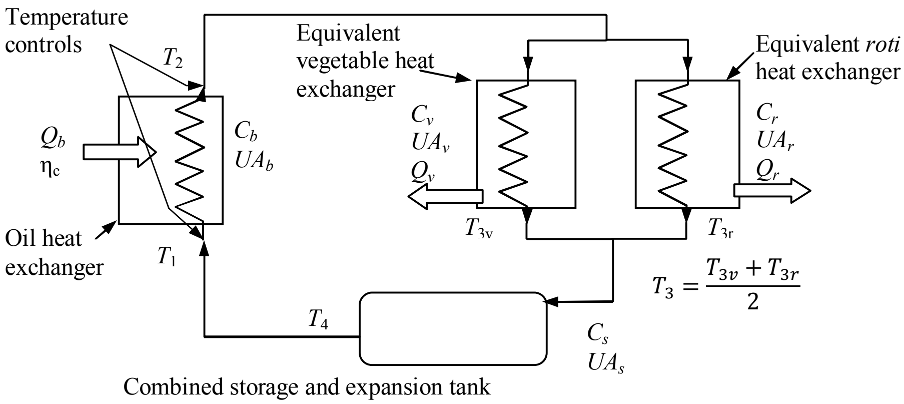

Figure 2: Schematic layout of cooking system for energy modelling

Therminol 55 circulates through cooking system with mass flow rate $\dot{m}$ without any accumulation. Operation of cooking system during data collection is under load, and temperatures of Therminol 55 at various locations are varying with time; therefore, system is modelled as unsteady state (Sukhatme and Nayak, 2008). Consider overall energy balance equation for unsteady state as:

$$Energy\ inlet - Energy\ outlet = Energy\ accumulated\ in\ the\ system \tag{1}$$

Equation 1 is applied to all the components such as oil heater, equivalent heat exchangers for *kadhai* and *tava*, and combined storage and expansion tanks. Each equation is solved numerically using Euler method to predict temperatures for next time steps. For each time step, increment in time is by step size, Δt of 30 seconds. Consider temperature T_1, inlet to oil heater at time t, is known, and outlet temperature T_2 at time t is predicted by simplifying Equation 1 applied to oil heater as follows:

$$T_2|_t = \frac{[\eta_c Q_b + \dot{m}C_{p1}(T_1|_t - T_a) + \dot{m}C_{p2}T_a + UA_b T_a]\frac{\Delta t}{C_b} + T_2|_{to}}{\left[1 + \dot{m}C_{p2}\frac{\Delta t}{C_b} + \frac{UA_b \Delta t}{C_b}\right]} \tag{2}$$

Where, $T_2|_{to}$ is temperature T_2 at previous time, and C_{p1} represents specific heat capacity of thermal oil at temperature T_1. Similarly, Equation 1 (energy balance equation) is appropriately proposed for equivalent heat exchangers of *kadhai*, *tava*, and combined storage and expansion tanks. The predicted various outlet temperatures are as follows:

$$T_{3v}|_t = \frac{\left[\frac{\dot{m}}{2}C_{p2}(T_2|_t - T_a) + \frac{\dot{m}}{2}C_{p3}T_a + UA_vT_a\right]\frac{\Delta t}{C_v} + T_{3v}|_{to}}{\left[1 + \frac{\dot{m}}{2}C_{p3}\frac{\Delta t}{C_v} + \frac{UA_v\Delta t}{C_v}\right]} \tag{3}$$

$$T_{3r}|_t = \frac{\left[\frac{\dot{m}}{2}C_{p2}(T_2|_t - T_a) + \frac{\dot{m}}{2}C_{p3}T_a + UA_rT_a\right]\frac{\Delta t}{C_r} + T_{3r}|_{to}}{\left[1 + \frac{\dot{m}}{2}C_{p3r}\frac{\Delta t}{C_r} + \frac{UA_r\Delta t}{C_r}\right]} \tag{4}$$

$$T_4|_t = \frac{\left[\dot{m}C_{p2}(T_3|_t - T_a) + \dot{m}C_{p3}T_a + UA_rT_a\right]\frac{\Delta t}{C_r} + T_4|_{to}}{\left[1 + \dot{m}C_{p3r}\frac{\Delta t}{C_r} + \frac{UA_r\Delta t}{C_r}\right]} \tag{5}$$

The system starts at time t equal to zero with temperatures of all components at ambient. For next time t_1 equal to Δt, temperature $T_1|_{t1}$ is considered to be known temperature equal to $T_4|_t$, (temperature T_4 at previous time) and using Equation 2, temperature $T_2|_{t1}$ can be predicted. For same time t_1, subsequently, $T_{3v}|_{t1}$, $T_{3r}|_{t1}$, and $T_4|_{t1}$ can be predicted using Equations 3, 4, and 5. Thus, by repeating same calculation procedure in each time interval, all temperatures can be predicted using simplified proposed energy model. The temperature control switches are introduced appropriately and it cycle off oil heater as per set temperatures. The trend of predicted model temperatures are matched with actual measured temperatures T_1 and T_2. From this, approximate values of heat capacity rate of thermal storage (C) and thermal conductance (UA) for various components such as oil heater, storage tank, and equivalent heat exchangers for *kadhai* and *tava* are determined. The equivalent heat duty used for vegetables and *roti* cooking are estimated approximately and variation of it with time is shown in Figure 3. These estimated appropoximate values can be further used to analyze energy conservation opportunities.

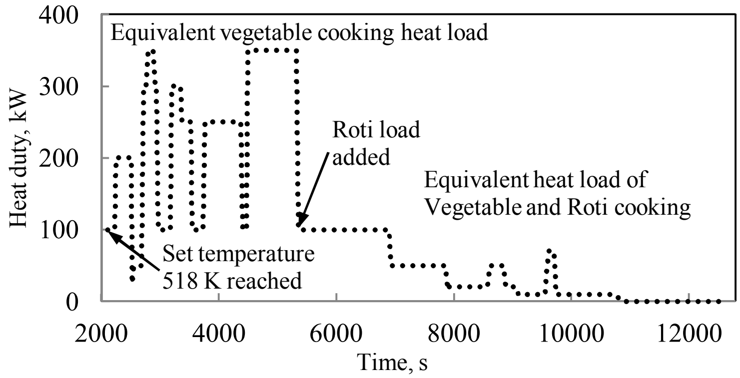

Figure 3: Equivalent heat load for vegetable and *roti* cooking

4. Energy conservation scheme

There is scope for energy conservation by using various schemes. One of the schemes discussed here is changing parallel to series-parallel configuration of heat exchangers (Bade and Bandyopadhyay, 2014) as shown in Figure 5a, b.

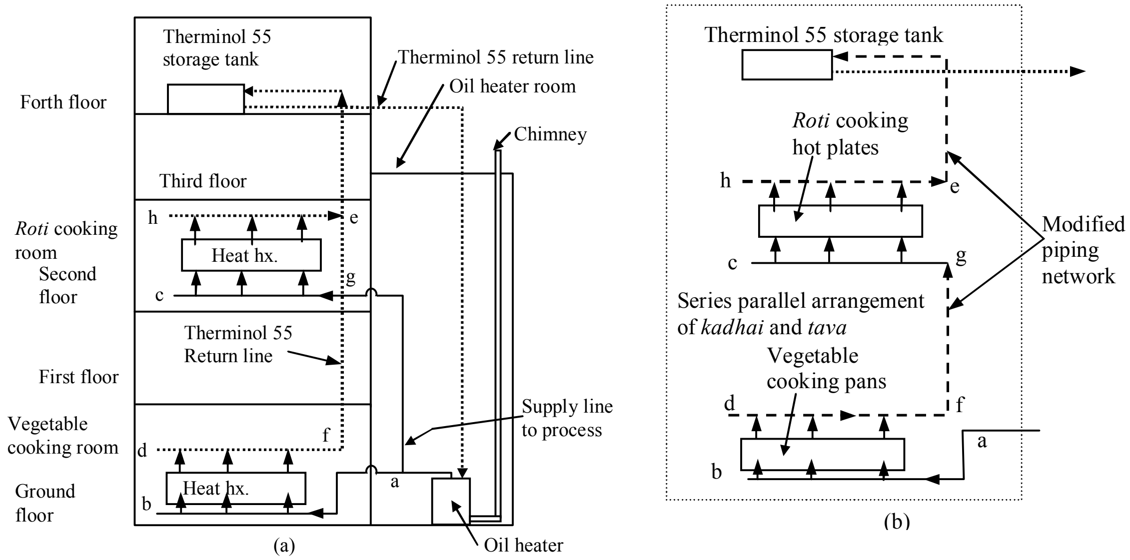

Figure 5: (a) Layout of cooking system and (b) layout modification (not to scale)

In current system, thermal oil is supplied to cooking pans (*kadhai*) and hot plates (*tava*) at same temperatures by parallel pipings as shown in Figure 5a. It may be possible to supply thermal oil in series-parallel combination by modification of heat exchangers provided temperatures and heat duty requirements are satisfied for maximum cooking load. General temperature required for vegetable cooking except frying of spices is 373 K. The temperature range for frying spices in cooking oil is 450-475 K for 5-10 minutes depends on type of vegetable oil. The vegetable cooking load is difficult to predict and is varies based on menu, and quantity of it. The modified arrangement for each *kadhai* and *tava* are in parallel, and set of *kadhai* and *tava* are in series as shown in Figure 5b. Due to this arrangement, there is less local fluctuation of temperatures for vegetable cooking. The temperature difference across *roti* cooking heat exchangers is small due to lower load, but temperature required is high around 515 K. Model of cooking system is modified for series-parallel combination of heat exchangers as: first vegetable cooking, and then *roti* cooking. Simulated model shows that series-parallel combination satisfies temperatures and heat duty constraints for current operating load of vegetable and *roti* cooking. As the thermal oil system is running under load, it is not possible to verify that whether proposed configuration will satisfy all cooking load conditions. With help of energy model, it is observed that for the same total heat load, diesel consumption is less for series-parallel combination compared to parallel combination by 4.5 kg per day, if cooking system runs thrice in a day for same operating conditions. Considering $1 per kg of diesel cost (in India) and system works round the year (365 days), annual saving in fuel cost is $1642. Total cost of piping, insulation, labor, and fittings (Ulrich and Palligarnai 2006) is $2681. The simple payback period comes to be 1.6 years. Due to change in parallel to series-parallel configuration, velocity of Therminol 55 through cooking pans, and hot plates will increase, which may enhance heat transfer capabilities with negligible increase in pumping power. During data collection, system is under load, so it is necessary to verify the temperature constraint for all load conditions, various vegetables, and maximum load condition before implementation of this modification.

5. Conclusion

Thermal oil based systems do not use water, so it is beneficial in water scarce regions in addition to other advantages. The simplified energy model is proposed for thermal oil based cooking system. The proposed model is dynamic in nature, which uses Euler method to predict temperature for next time step. The proposed energy model is helpful for simulation of energy conservation scheme. The presented energy conservation scheme of shifting parallel to series parallel configurations of heat exchangers enhances heat transfer capability due to increase in flow rate of thermal oil with negligible increase in pumping power. It shows saving in fuel with simple payback period of 1.63 years. There is potential energy conservation schemes, which may synthesized in detail to find energy conservation potential.

Acknowledgements

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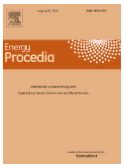

Biography

Mr. Mukund H. Bade is assistant professor in Mechanical Engineering Department at Sardar Vallabhbhai National Institute of Technology, Surat, India. He completed Ph. D. from Indian Institute of Technology Bombay, Mumbai, India. His area of interest is pinch analysis, energy efficiency, and energy modelling.

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Appendix A.

S.N.	Name of components	Specifications/features	Remarks
1	Oil heater	Rated capacity 697.83 kW- 2 Nos.	Thermax TPDi-06.
2	*Kadhai* (Cooking and frying pans)	1.2 m (W) × 0.38 m (H) 2 Nos. 1.5 m × 0.38 m 4 Nos. 1.8 m × 0.51 m 4 Nos.	Use: Vegetable cooking and frying in cooking oil
3	Roaster	0.9 m × 0.72 m 1 No.	Grind/mixing of groundnut, pulses, etc.
4	*Tava* (Hot plates)	1.95 m×0.9 m 8 Nos.	Use: Chapattis, dosa, etc.
5	Thermal oil	Trade name: Therminol 55	Maximum stable temperature 578 K